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THE ACCUMULATION AND STRUCTURAL DEVELOPMENT OF THE WIREGRASS (TETRARRHENA JUNCEA) FUEL TYPE IN EAST GIPPSLAND

RESEARCH REPORT No. 37
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SUMMARY

Wiregrass fuels, which form an elevated and highly flammable understorey in much of the economically valuable forest of the coastal and foothill areas of East Gippsland, Victoria, were measured and destructively sampled in clusters of 3-4 plots at 69 sites in 10 age classes. Negative exponential models fitted the data well and showed that after a fire the level of total fine fuel can be expected to reach 95 % of its average long-term value of 16 t/ha (comprising 6 t/ha elevated fuel and 10 t/ha surface fuel) in about 15 years, with half that level being reached in four years. Similarly, the fuel height and cover can be expected to reach 1.1 m and 67 % in 6.5 years, or half those levels in 1.5 years. Fuels reach the Department's existing prescribed maximum hazard levels for Protection Priority 1 Zones in four years and for Protection Priority 2 Zones in seven years; and remain low enough to provide some lesser protection for perhaps 10-12 years.

A strong relationship was established for predicting elevated fuel load from fuel height and (to a lesser extent) fuel cover; and surface fuel load was found to be correlated with fuel depth. These relationships should enable field personnel to appraise fuels readily and hence to meet the objectives of prescribed burn operations more effectively and with greater confidence.

The models were compared with those derived by multiple linear regression and were found to provide similar predictions. Negative exponential models that were fitted to the 0-10 year data were found to be suitable for predicting fuel levels over that 0-10 range of fuel ages.

Fire managers can use the models strategically to plan and monitor the protection provided by existing or future programs of fuel reduction burning. The protection of lives and of private and public assets, including a regrowth timber (especially sawlog) resource that is very succeptible to fire damage, may therefore increase and be more efficient.

INTRODUCTION

Large and uncontrollable wildfires burning in Very High to Extreme (FDI [1]25 - 100) conditions have been a feature of the recorded fire history in the Orbost Region of CNR (see Figure 1). In the period between 1973 to 1993, less than 5 % (44 out of 1023) of the recorded wildfires burnt 96 % (530547 out of 551998 ha) of the total area burnt, with two major fires at Cann River (1983) burning 46 % (253000 ha) of this area. Severe fires can occur any time between September and April, with dry lightning storms providing a regular source of ignition (CFL 1990). Future large wildfires would seem to be inevitable.

Very flammable understorey fuels contribute greatly to the fire danger[2] of the forests of East Gippsland. One of the most important to fire managers is the Wiregrass fuel type, which is widespread throughout the state forests of the coastal and foothills area (see Figure 1)[3]. These fuels are dominated by *Tetrarrhena juncea* (wiregrass) which forms an elevated web of grass like fibres that suspend fallen eucalypt litter and become intertwined with many other scrub species. The associated species typically include *Pteridum esculentum* (Bracken), *Platylobium formosum* (Handsome Flat Pea), *Ghania* spp (Saw Sedge), *Hakea sericea* (Silky Needlewood) and *Acacia terminalis* (Sunshine Wattle). When combined with heavy bark quantities on stringybark trees, this elevated and aerated fuel type is one of the most flammable in Australia (Buckley 1990)

In regrowth stands dominated by Silvertop Ash (*Eucalyptus sieberi*) and associated stringybark species (*Eucalyptus globoidea, Eucalyptus baxteri, Eucalyptus muellerana)* the wiregrass understorey is common. These stands with a predominant height of 30 m are susceptible to crown and stem damage by fire, which has the potential to reduce sawlog values by up to 80% if complete crown scorch occurs (Gill and Moore 1992). The protection of these forests against wildfire is economically important.

The intensity of (and hence damage caused by) a fire is substantially determined by the amount of fuel that is available to burn (McArthur 1958,1962,1967). Fuel reduction burning is used in strategic areas to maintain fuel quantities below the level at which a wildfire becomes difficult or impossible to control (Luke and McArthur 1978, Hodgson and Heislers 1972), and to reduce wildfire intensity and subsequent damage to timber resources and other values.

CNR aims to maintain fine fuel loads below critical ("trigger") levels of eight and twelve tonnes per hectare (t/ha) to assist in the control of wildfires at the respective fire danger indices of 50 (in Priority 1 burning zones) and 25 (in Priority 2 burning zones) (CFL 1988). In the Orbost Region, the trigger level system is applied to seventy percent (approximately 560300 ha) of the public land area (CFL 1990).

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[1] FDI refers to fire danger index, which is a standardised measure of daily fire risk that reflects daily fuel moisture and weather conditions. The FDI is expressed on a nominal scale from zero (at which a fire will not burn) to 100 (at which extreme fire behaviour will occur).

[2] "Fire danger is the resultant of all factors which determine whether fires will start, spread and do damage and whether and to what extent they can be controlled" (Luke and McArthur 1978).

[3] The Wiregrass understorey is not continuous in the zone outlined in Figure 1, but will usually cover 30 to 70% of any given burning unit.

The trigger level system is based on an assumption that the fuels mainly comprise surface litter, but the forests of East Gippsland are characterised by fuels that are elevated and aerated. When compared with a fire in surface litter fuels, the rate of spread, flame height and intensity of a fire in elevated fuel will be greater (Sneeuwjagt and Peet 1985, Cheney *et al* 1992). For a given fuel load, elevated fuels provide a greater fire hazard[4].

Models of fuel development provide information on the development of fire hazard with time (eg Peet 1971, Burrows and McCaw 1990), and hence the longevity of the effects of fuel reduction burning on fire behaviour. At the strategic level, fuel accumulation and structural development models are a necessary *tools* for monitoring the strength of a fuel reduction network that consists of a number of burning units of different fuel ages, and for planning and scheduling fuel reduction burning programs. Techniques for the prediction and assessment of the fire hazard of elevated wiregrass fuels are needed for the protection of regrowth forests in East Gippsland.

At the operational level, detailed knowledge of fuel types and fuel quantity is a factor that must be considered when developing fuel reduction burn prescriptions and ignition procedures for the implementation of prescribed burns in the silvertop and mixed species regrowth forests, so that control can be assured and damage minimised. The appraisal of wiregrass fuel levels in the field is difficult because fuel bulk density and fuel quantity vary a lot over short distances, so more time efficient techniques for the indirect estimation of wiregrass fuel quantities from factors such as litter depth (Sneeuwjagt 1971, Sneeuwjagt and Peet 1985), and from the height, cover and density of elevated fuels (Sneeuwjagt 1971, 1973, Kessel et al 1982, Sneeuwjagt and Peet 1985), are needed.

The aim of the present study is develop fuel accumulation and structural development models, and techniques for the indirect estimation of the wiregrass fuel quantities.

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[4] Fire hazard is the exposure or vulnerability to loss due to the effect a fuel complex has on ease of ignition, fire behaviour and suppression difficulty (Luke and McArthur 1978). The fuel components that can affect fire hazard include, fuel quantity (McArthur 1967), fuel height , fuel continuity (Cheney *et al* 1992), the proportion of dead to live material (Sneeuwjagt and Peet 1985), fuel particle surface-area to volume ratio and fuel bed bulk density (Rothermel 1972).

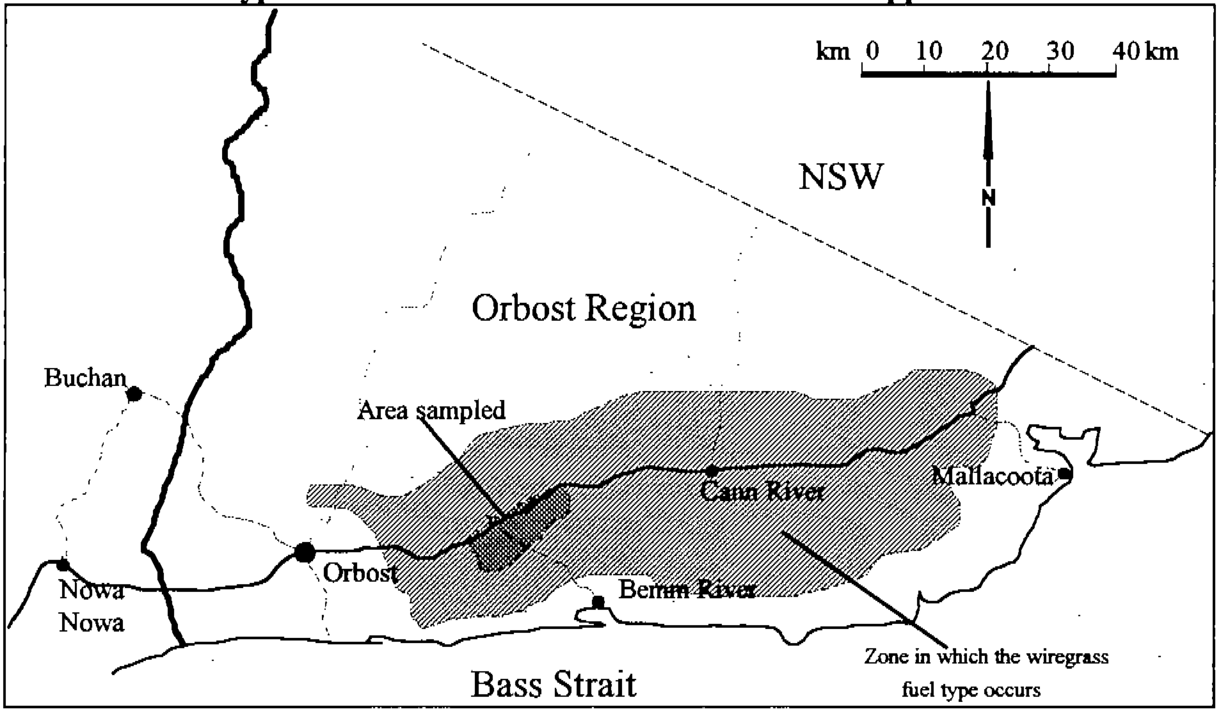
METHODS

Site selection

Wiregrass fuels were sampled in 25 to 40 year old Silvertop and mixed species regrowth forests situated on the Coastal and Foothills areas of East Gippsland. These forests are generally described by Land Conservation Council (1985) vegetation classifications of 3c, 3d and 3e which are in the structural classification of "open forest class III, 28 to 40 m" top height. Fuel sampling concentrated on sites 30 km east of Orbost that had been previously burnt by low intensity experimental fires of known coverage. These sites had not previously been burnt for 24 years and before being burnt the wiregrass fuels had reached a high level of development where the height averaged 1.2m and the total fuel quantity averaged 19 to 22 t/ha (Buckley 1990). Sites that had been burnt by a high intensity wildfire in 1968 where also sampled on the basis that the time elapsed since fire (24 years) should have been long enough[5] for fuel levels to reflect site factors and time since fire rather than the intensity of that fire. Wiregrass fuels with age four years and 24 years since fire are illustrated in Photograph 1 and Photograph 2 respectively.

Fuels were sampled at 1 to 16 points (total of 69 points) in each of ten classes of fuel age (see Figures 1 and 2). The location of sample points was determined randomly expect that gully fuels (the lower third of a slope) were excluded because the extent of fire penetration into these sites was variable and unknown.

Figure 1. Location of sample sites and approximate distribution of the wiregrass fuel type in the coastal and foothill forests of East Gippsland



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[5] Severe crown scorch causes heavy litter fall, and can increase fuel loads by up to five tonnes per hectare soon after fire, however litterfall subsequently declines when the scorched trees go through a crown rebuilding phase compensating for the early high levels of litter fall (O'Connell *et al* 1979). If two sites of the same fuel type/site productivity experience a high and low intensity fire respectively, then the fuel quantity at both sites will converge toward the steady state level if left unburnt for 35 years (Kessell *et al* 1984). The growth and development of fuels maybe different following a crown fire, because there is no litter left to fall after the fire, and because the understorey has less competition for sunlight and nutrients.

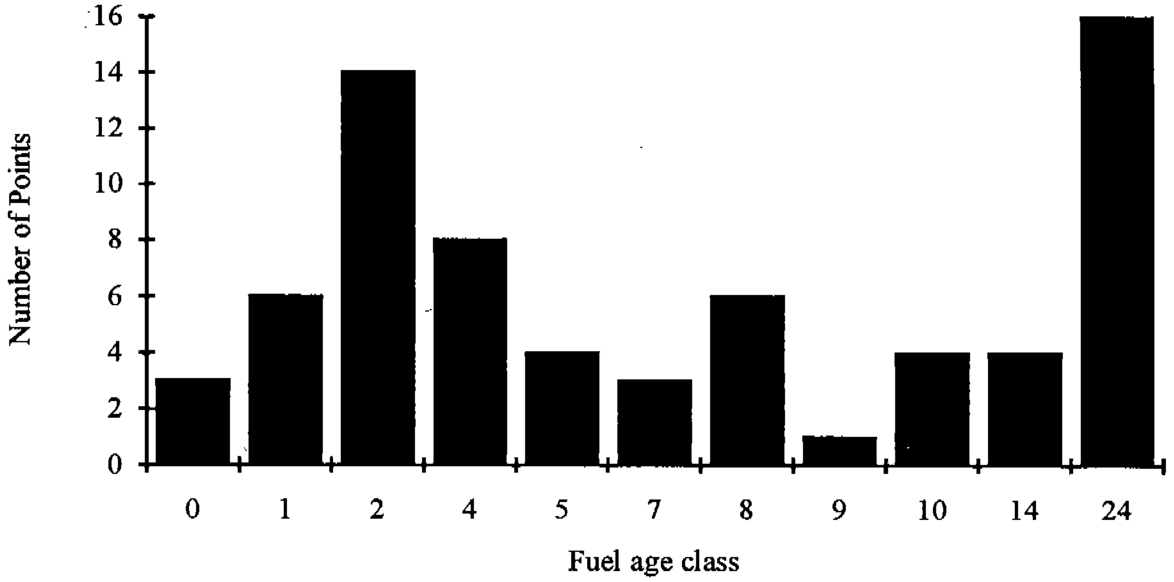

Figure 2. Summary of the number of fuel sampling plots in each age class

Fuel sampling techniques

At each sampling point, one 4 m x 1 m plot was established and divided into four 1 m x 1 m sub-plots from which elevated fuels were collected using mechanical hedgeclippers (as illustrated in Photograph 3) from all four sub-plots; then three samples of surface fuel were collected using a 0.1 m^2 sampling frame (as illustrated in Photograph 4) from the first three of those subplots that did not contain large logs or heavy branch debris. All dead and living material of thickness less than 6mm was collected. The distinction between elevated and surface fuels was as follows:

- *Elevated fuels* that consisted of shrub and juvenile overstorey plants, grasses, low shrubs, heaths and wiregrass containing suspended leaves, bark and twigs. In the oldest fuels sampled, fuel height sometimes reached 2 m but in most instances the wiregrass was continuous to an average height of 1.2 m. Fuel was collected above 1.2 m only if the fuel continuum was maintained.

- *Surface fuels* that consisted of leaf, twig and bark litter of the overstorey and understorey plants. The boundary between these fuel components was often unclear because surface fuels were suspended above the ground by the wiregrass web which was often continuous to the top of the standing scrub plants; and in these instances the surface fuels where sampled up to a depth of 10 cm above the soil only.

The sampling of elevated fuel in each sub-plot also included a measure of structural development characteristics that included average height (using a 2m height pole), a visual estimate of percentage cover and a subjective assessment of density class (Heavy, Moderate or Light). From the measure of average fuel height and fuel load, the bulk density (kg/m^3) of the sub-plots were calculated. From the surface fuel sub-plots, cover and density were also assessed, and fuel depth was taken to be the average of two measurements (using a fuel depth gauge) of the depth of the uncompressed litter bed. At each sampling point the following other factors were also recorded: slope (percent), aspect (degrees), basal area, estimate of crown cover (percent), stand type and the species composition of the overstorey.

The time needed at each sample location was 1 to $1^1/2$ hours (for two people), comprising 5 to 10 minutes for fuel measurement and description (ie litter fuel depth, and elevated fuel height, cover and density), 30 to 40 minutes for harvesting of elevated fuels (using a powered hedge trimmer) and 30 to 40 minutes for surface litter fuel sampling. Fuels were oven dried at 105°C to determine fuel moisture content (FMC); for surface fuels the whole sample was dried, whereas for elevated fuels the sample was air dried in a shed for one week and then weighed before three sub samples (20g of fuel in jars) were oven dried.

Data analysis

The data were primarily analysed using non-linear regression techniques (Mead and Curnow 1990, SAS/STAT Guide for Personal Computer Version 6, 1987). The main curve used was the negative exponential, which was outlined by Olsen (1963) for describing litter accumulation and decay in forest ecosystems on the theoretical basis that litter accumulation occurs rapidly in the initial period following fire but then subsequently slows or flattens to a plateau.

In Australian forests, the negative exponential model has been used by a number of authors studying fuel accumulation or nutrient cycling (Fox *et al* 1979; Kessel *et al* 1982; Birk and Simpson 1980; Sandercoe 1986, Raison et al 1986, O'Connell 1987, Burrows and McCaw 1990). The most frequently used, and the one used in the present study, is a modified version (Raison *et al* 1983) which assumes that immediately after fire the fuel load is zero (t/ha), and which can be expressed as follows:

$$X(t) = X^{ss} (1-e^{-kt})$$

where: $X(t)$ denotes the litter weight per unit area, t years after fire;
X^{ss} denotes the litter weight accumulated under steady state conditions;
k denotes the decomposition rate constant (y^{-1}).

In the present study the above model was used to describe the fuel accumulation (total, elevated and surface litter fuel load) and structural development data sets, and for the estimation of surface fuel load from litter depth. The observations that were used in the analysis were the averaged values from the sub-plots at each sampling point.

The negative exponential curve was also tested for fit to a reduced data set (0 - 10 years), so as to determine its applicability to fuel accumulation studies where sampling does not extend to fuels that are at "steady state" levels. These were compared with the models that where fitted to the complete data set (0 - 24 years) by visual inspection of graphs of the model curves plotted with the raw data points against time since fire, and by comparison of the asymptotic standard error values for the derived estimates of X^{ss} and k.

For comparison the fuel accumulation data were also analysed with multiple linear regression techniques, which involved the use of two or more independent variables (eg time since fire and basal area) to determine the factors that most influence the dependent variable (eg quantity of fine fuel). The distribution of the data was first inspected to determine the transformations that might be most suitable for fitting a linear model to a non-linear relationship (Ryan et al 1985). Multiple regression techniques were used to analyse fuel accumulation data and for the development of a model for the estimation of elevated fine fuel load from height and cover, for which the negative exponential relationship was inappropriate.

Tests for statistical significance of the multiple regression equations involved the use of t-tests (for significance of the intercept and coefficients of the predictor variables) and F-tests (for the significance of the whole model) at the 95 % significance level; and residuals were plotted against dependent and independent variables, and plots of the normalised distribution of the residuals were inspected for linearity (Draper and Smith 1981, Devore 1991). The F-test and t-test are not applicable to the non-linear models (Draper and Smith 1981), so model significance was assessed by the magnitude of the standard error values for the derived estimates of X^{ss} and k, and by comparison of the statistical significance of the most appropriate multiple regression model derived using the techniques described above.

The most appropriate model to fit to the fuel accumulation data was determined by comparison of the results from the non-linear and linear regressions through an inspection of the graphs of the residual values plotted against the independent variable (time since fire), because the R-square value and the asymptotic correlation matrix value generated by the linear and non-linear analyses are not directly comparable.

Photograph 1. Wiregrass fuels four years after fire. The total fuel load is 7 t/ha, which comprise 4 t/ha elevated fuel and 3 t/ha of surface litter. Note the four meter by one meter frame, that was used to define the plot area.

Photograph 2. Wiregrass fuels 24 years after fire. These fuels are heavier than average with a total fuel load of 18.5 t/ha, that comprise 9.5 t/ha of elevated fuel and 9 t/ha of surface litter. The average height of the elevated fuel is 1.8m and the cover is 80%.

Photograph 3 Destructive sampling of elevated fuels using mechanical hedge trimmers. The wiregrass fuels being samples are 24 years old, with a fuel load that comprise 8.1 t/ha of elevated fuel, and 13.7 t/ha of surface litter. The average height of the elevated fuel is 1.4m and the cover is 70%.

Photograph 4. Sampling frame ($0.1m^2$) used for the destructive sampling of surface litter fuels. The surface litter fuels being sampled are four years old, with a fuel load of 5.5 t/ha and a litter depth of 22 mm.

RESULTS

Fuel accumulation - negative exponential model

The non-linear models for predicting total, elevated and surface litter load after prescribed fire are plotted with the raw data in Figures 4, 5 and 6 respectively. The equations for these models are as follows:

- *Total fine fuel load(t/ha)* = $16.1(1-e^{-0.19\,t})$

  where $X^{ss}_{(95\%)} = 15.0 - 17.2$ {0.56}[6] and $k_{(95\%)} = 0.15 - 0.22$ {0.02}

- *Elevated fine fuel load(t/ha)* = $5.9(1-e^{-0.19\,t})$

  where $X^{ss}_{(95\%)} = 5.1 - 6.7$ {0.41}and $k_{(95\%)} = 0.11 - 0.25$ {0.04}

- *Surface fine fuel load(t/ha)* = $10.1(1-e^{-0.19*t})$

  where $X^{ss}_{(95\%)} = 9.1 - 11.1$ {0.51} and $k_{(95\%)} = 0.14 - 0.24$ {0.03}

These models suggest that in long unburnt (assumed to be steady state) fuels the total fine fuel load approaches 16 t/ha, comprising of 6 t/ha of elevated fine fuel and 10 t/ha of surface fine fuel, with 95% of these levels (denoted by "X^{ss}-95%") being reached at 15, 16 and 14 years. after fire respectively. The models also predict that these three components of fuel will reach half the long unburnt levels (denoted by "X^{ss}-50%") within 4 years.

The equations for the reduced data set are as follows:

- *Total fine fuel load(t/ha)* = $13.9(1-e^{-0.26\,t})$

  where, $X^{ss}_{(95\%)} = 11.8 - 15.9$ {1.02} and $k_{(95\%)} = 0.17 - 0.34$ {0.04}

- *Elevated fine fuel load(t/ha)* = $7.0(1-e^{-0.14\,t})$

  where, $X^{ss}_{(95\%)} = 3.4 - 10.7$ {1.80} and $k_{(95\%)} = 0.02 - 0.26$ {0.06}

- *Surface fine fuel load(t/ha)* = $7.7(1-e^{-0.35\,t})$

  where, $X^{ss}_{(95\%)} = 6.2 - 9.2$ {0.74} and $k_{(95\%)} = 0.18 - 0.52$ {0.09}

When compared with the analysis of the complete data set, the models for the reduced data set suggest that the maximum value for elevated fine fuel load (7 t/ha) is higher, but for total (14 t/ha) and surface fine fuels (8 t/ha) the maximum value is lower. The models fitted the reduced and complete data set well across the range of data that was analysed (see Figures 4, 5, 6), but the asymptotic standard error values for the estimate of the steady state fuel load ($X^{ss}_{(95\%)}$) are higher for the reduced data set, indicating that the model fit is not as good.

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[6] Values in parenthesis {} are asymptotic standard error of estimate values for negative exponential models, and standard error of estimate values for multiple regression models.

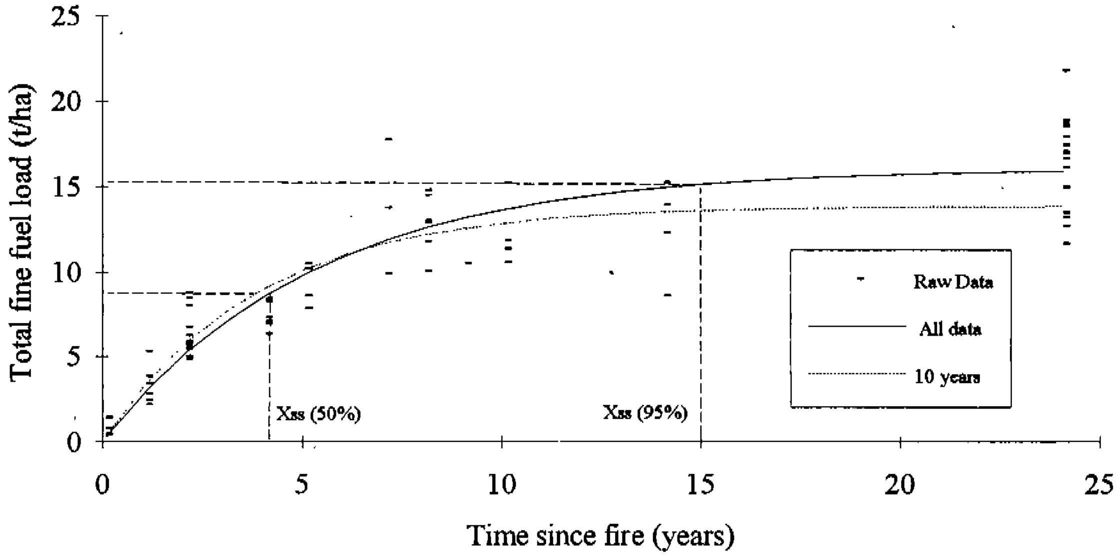

FIGURE 4. The relationship between *total fine fuel load* and *time since fire* for all data and a reduced data set (0 - 10 years).

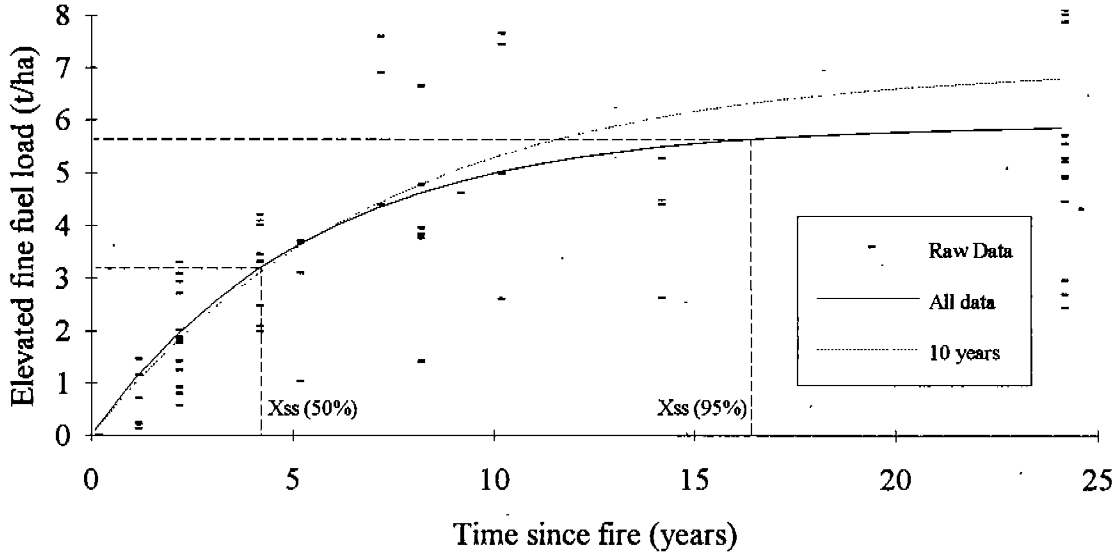

FIGURE 5. The relationship between *elevated fine fuel load* and *time since fire* for all data and a reduced data set (0 - 10 years).

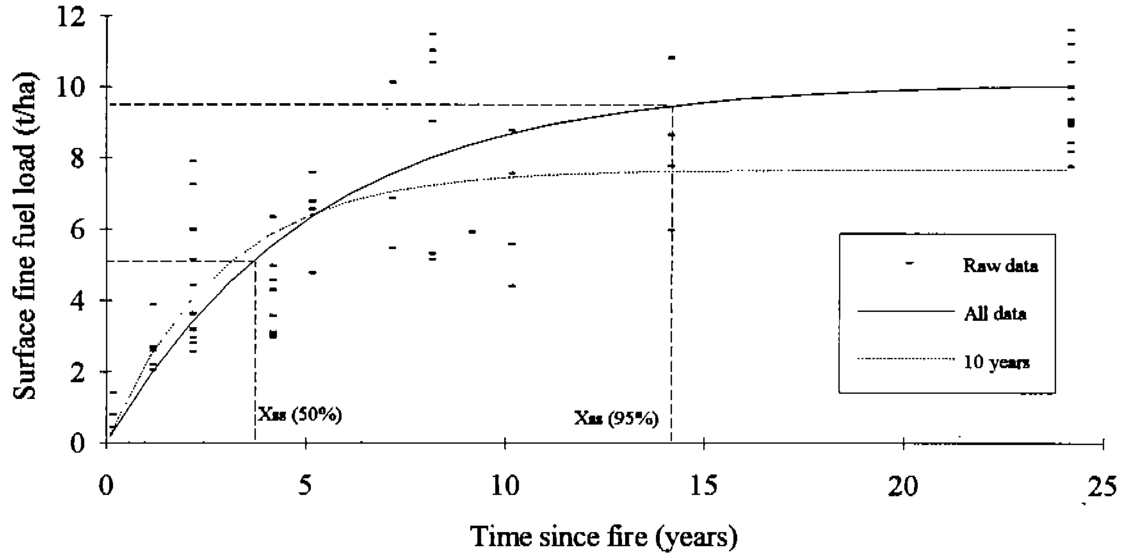

FIGURE 6. The relationship between *surface fine fuel load* and *time since fire* for all data and a reduced data set (0 - 10 years).

Fuel structural development

For the prediction of the fuel structural development (ie. bulk density, fuel height and fuel cover) the most important variable was time since fire. The following equations, the curves of which are plotted in Figures 7-9, were derived:

- *Bulk density(kg/m³)* = $0.5(1-e^{-0.31\,t})$

  where $X^{ss}_{(95\%)} = 0.4 - 0.6\ \{0.03\}$ and $k_{(95\%)} = 0.31 - 0.06\ \{0.06\}$

- *Fuel height(m)* = $1.1(1-e^{-0.47\,t})$

  where $X^{ss}_{(95\%)} = 1.1 - 1.2\ \{0.05\}$ and $k_{(95\%)} = 0.32 - 0.62\ \{0.07\}$

- *Elevated fuel cover (%)* = $71.6(1-e^{-0.46\,t})$

  where $X^{ss}_{(95\%)} = 66.1 - 77.0\ \{2.7\}$ and $k_{(95\%)} = 0.33 - 0.60\ \{0.06\}$

The predicted average values for long unburnt fuels were 0.5 kg/m³ for fuel bulk density, 1.1 m for fuel height and 72 % for fuel cover. The models predict that X^{ss}-95% of those levels were reached at 13, 6.5 and 6.5 years respectively; and that the X^{ss}-50% levels were achieved after 2, 1.5 and 1.5 years respectively.

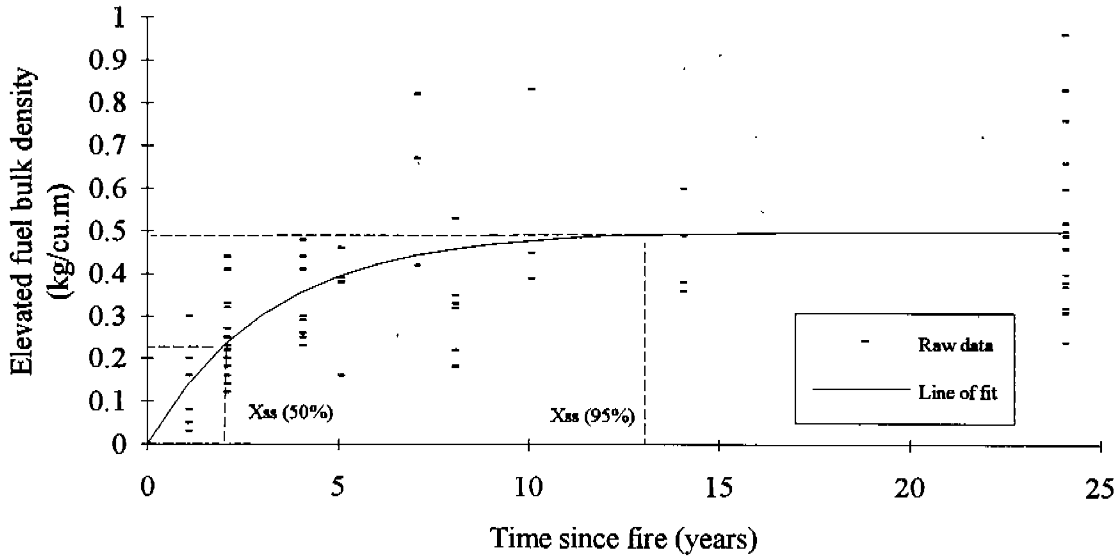

FIGURE 7. **The relationship between *elevated fuel bulk density* and *time since fire.***

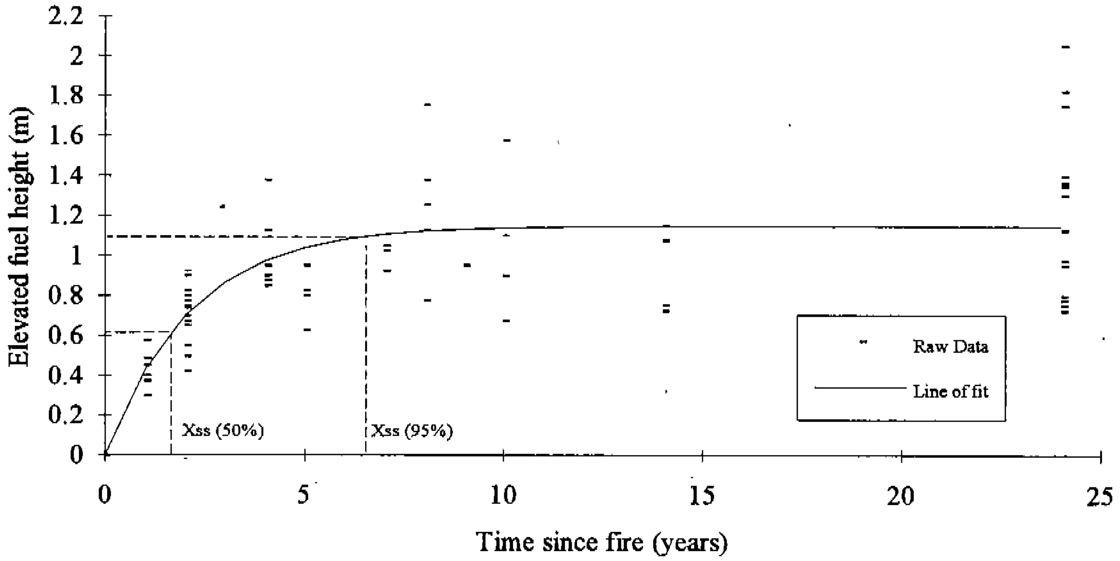

FIGURE 8. **The relationship between *elevated fuel height* development and *time since fire.***

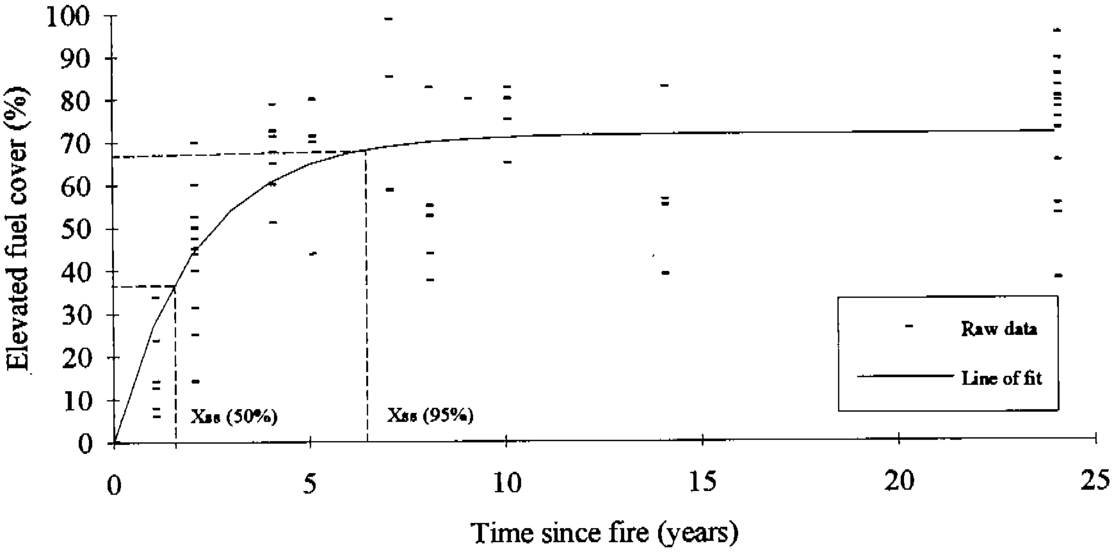

FIGURE 9. The relationship between *elevated fuel cover* development and *time since fire.*

Indirect estimation of fuel quantity

The following non-linear relationship was determined for the indirect estimation of surface fuel load from litter bed depth and is plotted in Figure 10:

- *Surface fuel load(t/ha)* $= 11.8(1-e^{-0.023\ d})$

where d is surface litter depth (mm),

$X^{ss}_{(95\%)} = 9.92 - 13.7\ \{0.95\}$ and $k_{(95\%)} = 0.016 - 0.031\ \{0.00\}$

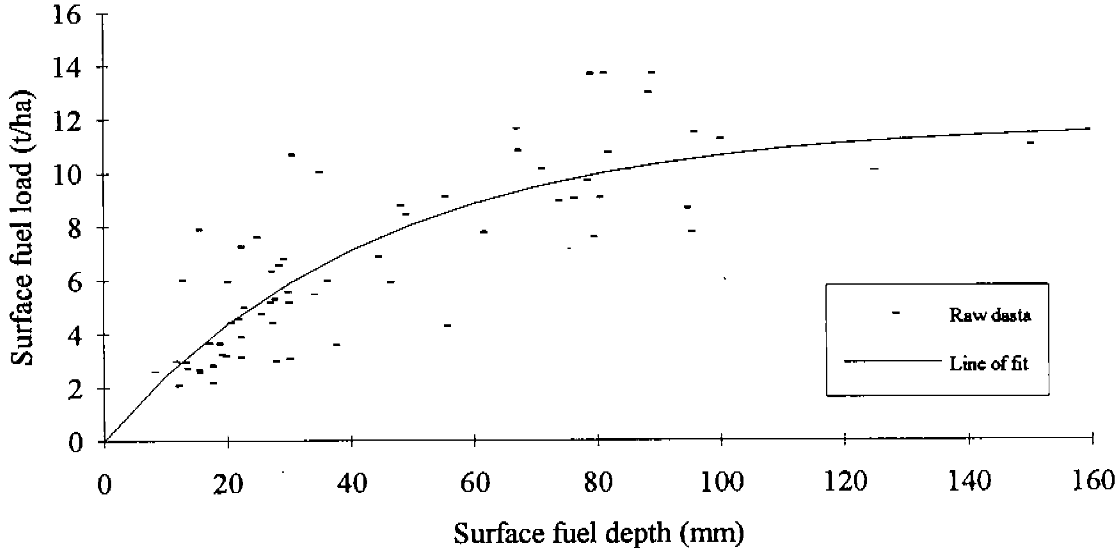

FIGURE 10. The relationship between *surface fine fuel load* and *fuel bed depth.*

Elevated fuel load was best predicted by fuel height, with the addition of fuel cover further improving the model (increasing the R^2 value from 75.7% to 89.5%). Multiple regression techniques were used to derive the following equation, with standard errors shown in brackets below the coefficients:

- *Elevated fuel load(t/ha)* = $e^{(-3.06 + 0.33\mathrm{sqrt}(c) + 1.69\mathrm{sqrt}(h))}$ $R^2 = 89.5$. (p=0.000)

  {0.19}{0.03} {0.33}

where: c is cover (%)
h is height (m)

Figure 11 illustrates the observed values and those predicted by the above equation. Visual comparison of this graph with the graph of the model that included only height indicated that the addition of fuel cover improved the capacity of the model to account for a number of data points that were the fuel load was greater than 5 to 6 t/ha.

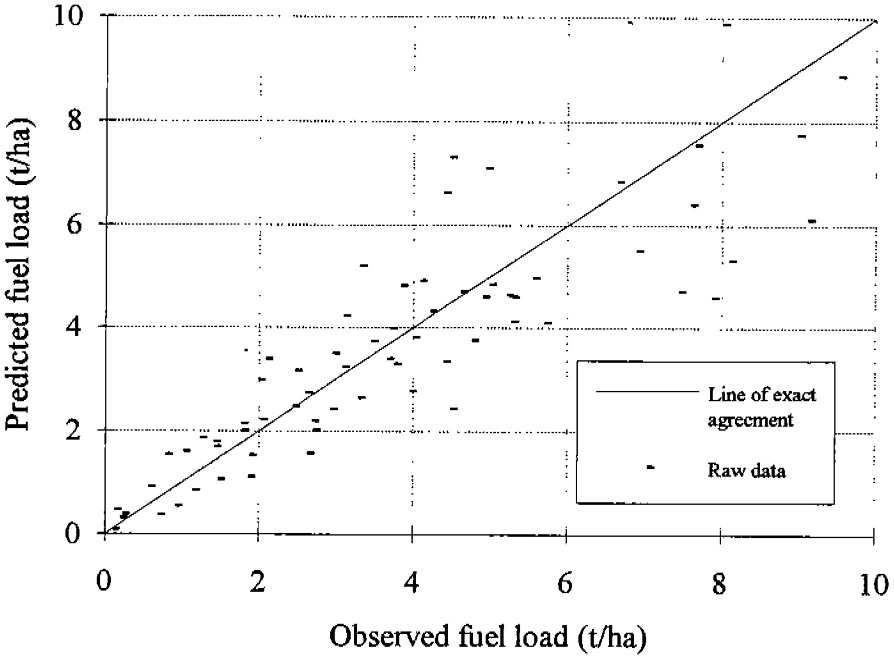

FIGURE 11. Plot of *predicted* versus *observed* values from the indirect estimation of *elevated fuel load* from *fuel height (m)* and *cover (%)*

Fuel accumulation - multiple regression techniques.

The analysis of the fuel accumulation data using multiple regression techniques found that the only significant independent/predictor was time since fire. The transformation of fuel load (square root) and time since fire (natural logarithm) produced the following models:

- *Total fine fuel load(t/ha)* = $(2.02 + 0.63 * \ln(t))^2$ $R^2 = 86.5$ (p = 0.000)

  {0.06} {0.03}

- *Elevated fine fuel load(t/ha)* = $(0.99 + 0.47 * \ln(t))^2$ $R^2 = 68.8$ (p = 0.000)

  {0.08} {0.04}

- *Surface fine fuel load(t/ha)* = $(1.70 + 0.46 * \ln(t)^2$ $R^2 = 72.9$ (p = 0.000)

  {0.07} {0.03}

The models are plotted in Figures 12 - 14. The addition of basal area statistically improved the prediction of surface fine fuel load (t/ha), but the magnitude of the change to predicted values was small and the need to collect additional data to use that model was great, so the more simple model was adopted. The models were consistent with the negative-exponential models, with total fine fuel increasing rapidly to 8 t/ha within 4 years and 16 t/ha in long unburnt fuels. A comparison, shown in Figure 15, of the distribution of the residual values from the linear and non-linear analyses of the total fuel accumulation data confirms that both models provide a reasonable fit to the data.

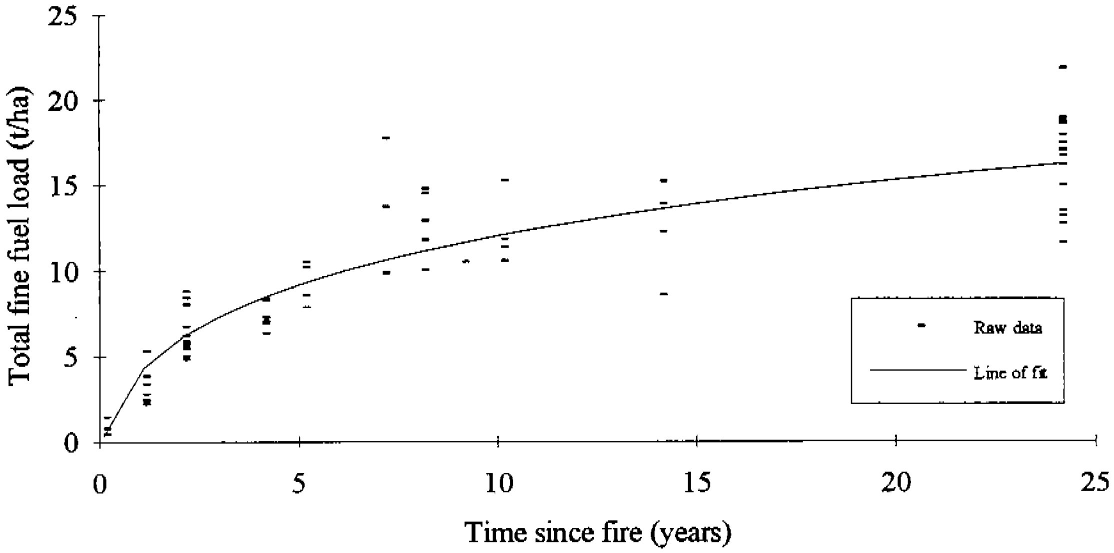

FIGURE 12. The relationship between *total fine fuel load* and *time since fire.*

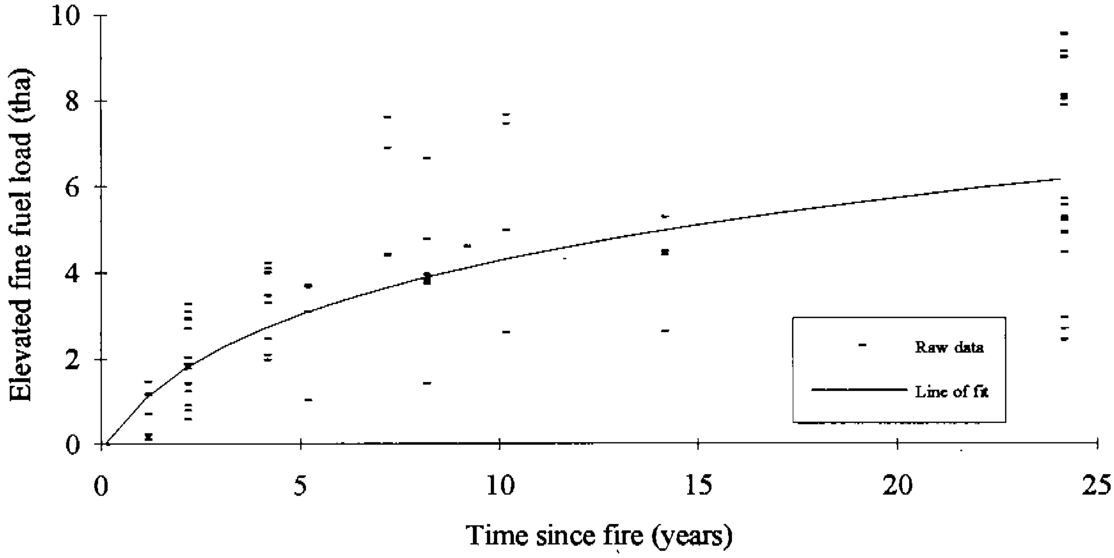

FIGURE 13. The relationship between *elevated fine fuel load* and *time since fire.*

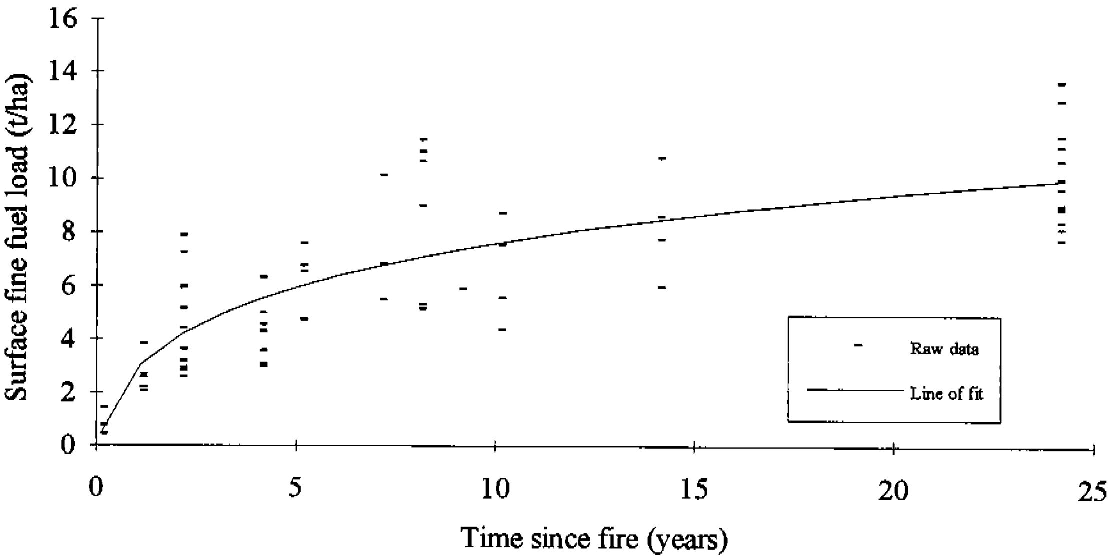

FIGURE 14. The relationship between *surface fine fuel load* and *time since fire.*

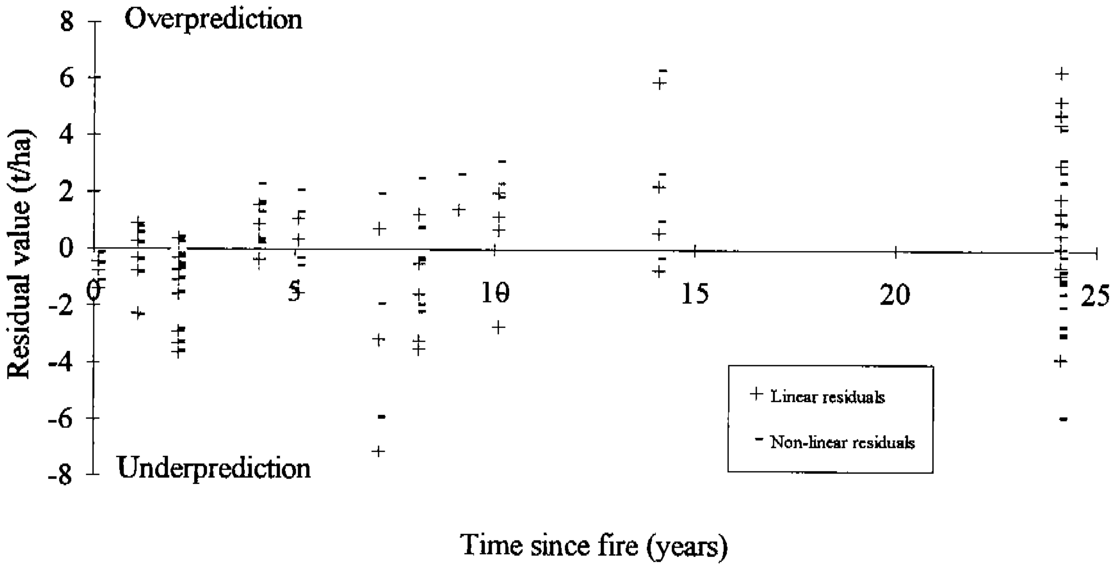

FIGURE 15. The distribution of *residuals* versus *time since fire* generated by the *linear* and *non-linear modelling* techniques when applied to *total fine fuel accumulation data.*

The development of fire hazard

The increase in fire hazard with time can be represented in a simple form by plotting the growth or development of fuel quantity and fuel structure as a percentage of the levels achieved in long unburnt fuels, as in Figure 16. This suggests that a degree of physical change to the fuel complex from fuel reduction burning may persist for 18 years, but that most of the change is reversed between 7 and 15 years, the time when X^{ss}-95% is reached for fuel structure and fuel load respectively. An important component of fire hazard not included in this analysis is the ratio of dead to live material in the elevated fuel component, this was observed to increase from four and until about 10 years after fire.

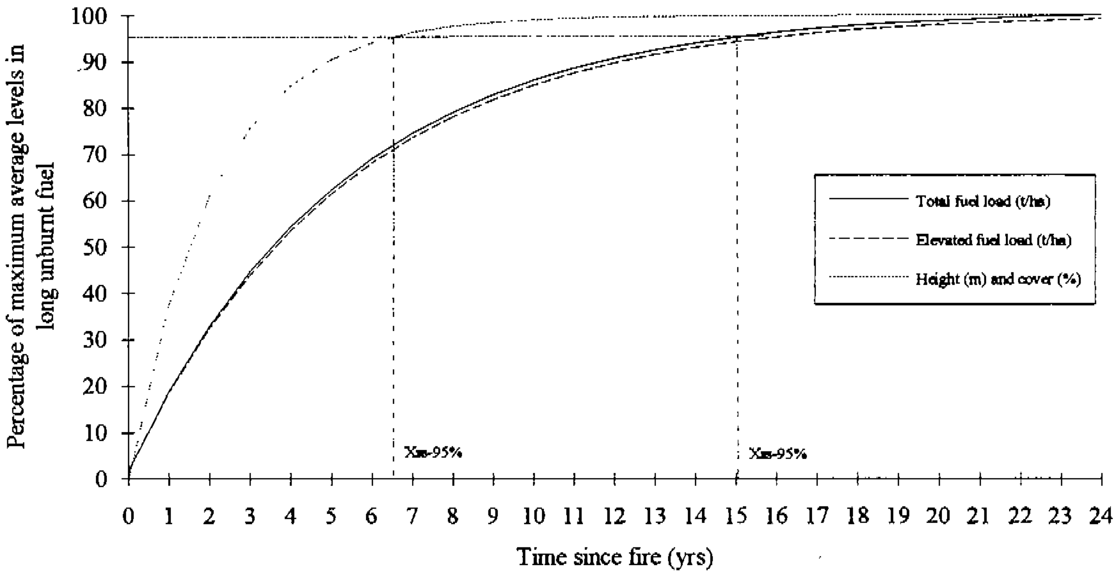

FIGURE 16. The development of *fuel hazard* (*structure* and *load*) expressed as a percentage of the maximum (X^{ss}) predicted values against *time since fire*.

DISCUSSION

Linear versus non-linear regression analysis

Figures 4 to 10 indicate that the fuel accumulation and structural development models provide a good fit to the data, and while the negative exponential models can not be statistically validated using tests applied to the linear models (ie F-Ratio test, T-value test) (Draper and Smith 1981), the corresponding linear approximations were all significant at the 95% significance level with R^2-values of between 60% (for bulk density) and 86% (for total fine fuel load). It can be reasonably expected that the negative exponential models are also significant.

Despite the similarity in fit of the non-linear and linear models, there are some important differences between using these two approaches for the analysis of fuel accumulation data. Multiple linear regression, which was used by Peet (1971) in Jarrah (*Eucalyptus marginata*) and Karri (*Eucalyptus diversicolor*) forests, enables the production of an analysis of variance for a number of independent variables but requires the use of complex transformations of the variables to approximate the negative-exponential relationship. The negative exponential model which has been used by many authors (eg. Fox *et al* 1979, Birk and Simpson 1980, Kessel *et al* 1882, Perala and Alban 1982, Sandercoe 1986, Raison *et al* 1983, Burrows and McCaw 1990) has a stronger theoretical basis (ie. fuel quantities rise quickly after fire and then increase slowly to a plateau level) but relies on the following assumptions:

- that a steady state relationship exists between litterfall and litter quantity on the forest floor (Hutson 1985) and therefore that the rate of decomposition is constant (Olsen 1963, Perala and Alban 1982),
- that litter fall is constant throughout the year (Olsen 1963)
- that all fuel is removed by fire (Sandercoe 1986)

These assumptions have been found to be violated, in eucalypt forests. A forest that is growing and changing its age and structure will gradually change its rate of litter fall and decomposition pattern so that a true steady state conditions may occur only in mature forests that have not been disturbed for 30 to 40 years (Birk and Bridges 1989, Birk and Simpson 1980). Even in mature and long unburnt forests, seasonal and annual differences above and below an "average" steady state fuel load can occur (Tolhurst *et al* 1992), because litter fall varies seasonally (Birk and Bridges 1989; McColl 1965; Birk 1979) depending on fluctuations in temperature and to a lesser extent, rainfall (Attiwill *et al* 1978), and decomposition rates vary with rainfall (Hutson and Veitch 1985, Raison *et al* 1986). However, despite the violation of the various assumptions, the negative exponential model is very useful, and is the most appropriate model for the analysis of the fuel accumulation data.

The models show that the rate of fuel accumulation is greatest over the first ten years. The greatest efficiency in sampling for the development of future models may be achieved by concentrating the sampling on the first ten years after fire (for example by sampling in 2 year intervals from 0 to 10 years), and then less intensively sampling fuel to 35 years after fire. If *all* sampling is concentrated within the first ten years, the decomposition constant (k) and steady state fuel (X^{ss}) values are not valid estimates of forest productivity, but the models would still be reliable predictors of fuel levels within ten years of a fire.

Fuel hazard development

The models predict that four years after fire total fuel load will reach 8 (□+/- 1.6)[7] t/ha, fuel height 1m, and elevated fuel cover 55%. They also predict that seven years after fire fuel load will reach 12 (□+/- 1.9) t/ha, fuel height 1.1m and fuel cover 69%. Changes in other factors such as bark and the proportion of fuel that is dead were not measured, but observations in the field suggest that dead material in the elevated fuel component accumulates rapidly from about four years, and hence that the flammability of the wiregrass fuel complex also increases rapidly. Within the respective 4 and 7 year periods, the prescribed protection levels for the Priority 1 and Priority 2 zones will be confidently reached and probably exceeded.

Burning Protection Priority 1 areas every four years may be operationally difficult, because the conditions that are necessary for a fire to sustain itself in younger and relatively less flammable fuels, are such that any escapes into adjacent older fuels would be difficult to control. To conduct these burns safely, greater preparation and resources would be needed; or alternatively, areas adjacent to Priority 1 zones could be burnt perhaps every 10 - 12 years to reduce the risk of escapes.

In Protection Priority 2 or Priority 3[8] burning zones, given that fuels accumulate to prescribed limits in seven years, resource constraints may make it difficult for all of the scheduled burning to be completed. However, the models and other observations show that fire reduces the fire hazard for perhaps 10 - 12 years, and the wildfire evidence from Buckley (1990) confirms that some protection will clearly extend for longer than seven years. Fire managers should ensure that the prescibed level of protection in the most strategic areas[9] is achieved, while recognising that in other parts of the zone a lesser level of protection will persist for up to 10-12 years.

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[7] The values in brackets represent the 95 % confidence limits using the upper and lower 95% k and X^{SS} estimates. The values are not true confidence limits, but are greater than those predicted using linear regression techniques and will provide an adequate measure of the confidence of the predicting the total fuel load accumulated after fire.

[8] Protection Priority 3 Zones have the same "trigger" levels as Protection Priority 2 Zones (12t/ha), but the area to be treated by fuel reduction is up to 50 %, compared with up to 80% for Priority 2.

[9] Note that some of the Protection Priority 2 Zones are wide enough that fuels need be kept below the prescribed protection levels in only half the width of the zone. Burning can then be scheduled to alternate between the two halves of the zone so that each particular burning unit is burnt less often. This can also be achieved by occasionally burning units in Protection Priority 3 zones that are adjacent to Priority 2 Zones.

Indirect techniques for fuel measurement

The fuel accumulation models provide an excellent tool for *scheduling* fuel reduction burns, but do not provide adequate information for the actual *conduct* of a burn. Successful implementation of a fuel reduction burn in regrowth forests requires a detailed knowledge of the fuel characteristics to assist in the formulation of an ignition pattern that ensures the burn is completed under suitable weather and fuel moisture conditions, so that unacceptable damage to crowns and stems is avoided.

Appraisals of wiregrass fuels by destructive sampling are rare because they are difficult and time consuming. Destructive sampling of elevated fuel takes in excess of one hour (for two people) at each sample point even when powered hedge trimmers are used, and further time is required for determining fuel moisture content. In comparison, the indirect estimation of fuel quantity from height and cover measurements and of surface litter quantity from depth takes 10 minutes, and the results are available immediately, irrespective of moisture conditions and time of the year. The speed of indirect techniques enables field staff to sample a large enough area at a number of sites to account for the high levels of localised variation commonly experienced on a fuel reduction burn unit to provide an adequate estimate of fuel quantity.

Indirect measurements for the estimation of fuel load have been successfully used by other land management agencies in Australia (Sneeuwjagt 1971, Kessel et al 1982, Sneeuwjagt and Peet 1985), but to be successful fuels need to be relatively homogeneous (McCaw 1988). The wiregrass fuel type is not homogeneous, but the use of a clustered sampling technique in the present study has provided a sufficient level of accuracy for the indirect estimation of fuel quantity which will enable operational fire personnel to conduct fuel reduction burns with a greater level of control and safety.

CONCLUSION

Techniques for the prediction and assessment of fire hazard in the wiregrass fuel type have been developed. At the planning and operational levels, these techniques will assist fire managers to protect the economically valuable regrowth timber resources of East Gippsland. Information on the development of fire hazard with time since fire indicates that CNR "trigger" levels for Protection Priority 1 and 2 Zones are reached in four and seven years respectively, but when compared with long unburnt fuels, the fire hazard of fuel reduced areas may be lower for perhaps 10 -12 years.

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APPENDIX 1 PROCEDURE FOR THE INDIRECT MEASUREMENT OF WIREGRASS FUELS

Use of Fuel Load Prediction Tables.

Within the area of interest, identify the major fuel types and choose three sampling sites within each. The choice of site may be random or may reflect fuels of particular interest, such as those which are relatively heavy or light, or which are located near control lines. Assess the surface and elevated fuels at each site as described in **(A)** and **(B)** below:

(A) Elevated Fuel

Materials:

1. Clip board and recording sheets.
2. 2m height stick.
3. 1m measuring stick.
4. 5 pig-tail pins.
5. Pocket calculator

Procedure :

1 Establish a 4m by 1m plot, with the 4m axis aligned in the direction of a random compass bearing.
2. Use the four pig-tail pins and the height stick to mark out a 1m by 1m sub-plot within one end of the 4m by 1m plot.
3. In each of the sub-plots measure the *average height* (m) of the elevated fuel and estimate percentage *cover* as described below:
    (a) use the height stick to measure the height of the tallest and shortest clumps of elevated fuel within the sub-plot and record the average of these values. When assessing the highest and lowest fuels do not include strands of wiregrass fuel above the main fuel bed or shrubs that are more than 1.5 above the main fuel bed; and in mature fuels, ignore small isolated heaths, forbes or grasses. If the elevated fuel bed is greater than 2m tall, assume that 2m is the average height.
    (b) first, estimate the proportion of the ground area that is covered by a dense mat of wiregrass - that estimate is the *percentage cover* (see Example 1). Then, *if the wiregrass is sparse or absent*, estimate the *net* proportion of the ground area that is covered by a shrub canopy (see Example 2). The aim is to estimate the proportion of the ground area that would actually be *shaded* by foliage cover if the sun was directly overhead - hence the gaps between the leaves on a shrub are not counted in the cover estimate.

Example 1 (left) illustrates a dense wiregrass mat that covers about 40% of the sub-plot - so the cover estimate is 40%. Example 2 (right) illustrates shrub foliage that covers about 30% of the area of the sub-plot, where the density of that cover is only about 20% - so the cover estimate is about 6%.

4. Record the results from the 4 sub plots on the "INDIRECT ESTIMATION OF WIREGRASS FUELS -Sampling Form", and then add up and divide by 4 the results from the 4 sub-plots. This will provide the average fuel height (m) and the average fuel cover (%) for the whole 4m by 1m plot.
5. Use Table 1 to estimate elevated fuel load (t/ha), by locating the junction of the average fuel height and cover value for the whole plot, and then reading off the estimated fuel quantity (t/ha).

(B) Surface Fuel

Additional Materials :

1. A fuel depth gauge.

Procedure :

1. Within the first three 1m by 1m sub-plots, find a patch of fuel that contains only surface litter fuel, as close as possible to the centre of the sub-plot. Place a pig-tail pin at the centre of this patch.
2. At two points 10cm each side of the pig-tail pin measure the depth of the fuel bed. Do not push the depth gauge down on the fuel bed, but press loose strands of wiregrass or leaves down to the top of the fuel bed.
3. If elevated fuels cover more than three of the 1m by 1m subplots, establish the surface litter sub-plots in adjacent areas (where the elevated fuels are absent), 1m apart in the direction of alignment of the 4m by 1m plot
4. Record the two depth measurements from the three surface litter sub-plots, and add these all up and divide the total by six to determine the average fuel depth.
5. Use the average fuel depth for the whole plot to estimate the fuel load (t/ha) from Table 2.

INDIRECT MEASUREMENT OF WIREGRASS FUELS: Prediction Tables.

Percentage Cover	Elevated Fuel Height (m)														
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6
10	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.7	*	*	*	*	*	*	*
20	0.4	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1	1.2	*	*	*	*	*
30	0.6	0.7	0.8	0.9	1.1	1.2	1.3	1.5	1.5	1.7	1.8	2.0	*	*	*
40	0.8	1.0	1.1	1.2	1.4	1.6	1.7	1.9	2.0	2.2	2.4	2.6	2.8	3.0	*
50	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.5	2.6	2.8	3.1	3.3	3.6	3.8	*
60	*	1.5	1.8	2.0	2.2	2.5	2.7	3.1	3.3	3.6	3.8	4.1	4.5	4.8	5.1
70	*	1.9	2.2	2.4	2.7	3.0	3.4	3.8	4.0	4.4	4.7	5.1	5.5	5.9	6.3
80	*	*	*	3.0	3.3	3.7	4.1	4.6	4.9	5.3	5.7	6.2	6.6	7.1	7.6
90	*	*	*	*	*	4.4	4.9	5.5	5.8	6.3	6.8	7.4	7.9	8.5	9.1
100	*	*	*	*	*	*	*	6.5	6.9	7.5	8.1	8.7	9.4	10.1	10.8

Table 1. The prediction of *elevated fuel load* (t/ha) from *percentage cover* and *average height*(m) of the elevated fuel complex.

	Surface Fuel Depth (mm)														
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
Fuel Load (t/ha)	2.4	4.4	5.9	7.1	8.1	8.8	9.4	9.9	10.3	10.6	10.9	11.1	11.2	11.3	11.4

Table 2. The prediction of *surface fuel load* (t/ha) from *litter bed depth* (mm)

INDIRECT MEASUREMENT OF WIREGRASS FUELS: Sampling Form

Location : ______________________ Burn Number: _______
Sampler(s) : ______________________ Date: ______________

Plot No: ______________________ Fuel Description: ______________
Bark Hazard Class: M/H/VH/E Average Stand Height (m): _______

Elevated Fuel

Subplot	Height (m)	Cover (%)	Fuel Load
1			▨
2			▨
3			▨
4			▨
Average			

Surface Fuel

Subplot	Depth (mm)	Fuel Load
1 A B		▨
2 A B		▨
3 A B		▨
Average		

Plot No: ______________________ Fuel Description: ______________
Bark Hazard Class: M/H/VH/E Average Stand Height (m): _______

Elevated Fuel

Subplot	Height (m)	Cover (%)	Fuel Load
1			▨
2			▨
3			▨
4			▨
Average			

Surface Fuel

Subplot	Depth (mm)	Fuel Load
1 A B		▨
2 A B		▨
3 A B		▨
Average		

Plot No: ______________________ Fuel Description: ______________
Bark Hazard Class: M/H/VH/E Average Stand Height (m): _______

Elevated Fuel

Subplot	Height (m)	Cover (%)	Fuel Load
1			▨
2			▨
3			▨
4			▨
Average			

Surface Fuel

Subplot	Depth (mm)	Fuel Load
1 A B		▨
2 A B		▨
3 A B		▨
Average		

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